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The mechanical behaviour of adhesively bonded composite joints under repeated axial impacts at different temperatures

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Abstract: In this study, the failure strength of single-lap adhesively bonded joints was investigated. The glass fibre epoxy composites used as adherends were manufactured by using a vacuum-assisted resin infusion method. These composites were bonded with a commercial material of epoxy-adhesive DP-460, which can be cured easily at room temperature. The specimens were built by bonding, and then repeated axial impact loads having various energy levels (0, 5, 10, 15, and 20 J) were implemented to the single-lap adhesively bonded composite joints at different temperatures (-20°C , 0°C , 20°C , 40°C , and 60°C). Subsequently, the specimens were exposed to static tensile loading at the same temperatures as those applied during the primary impacts. The variation in failure loads due to the effects of repeated axial impact loadings at different temperatures were investigated. Generally, the increase of impact energy level from 0 to 20 J leads to a gradual decrease in failure loads at all temperature levels except for the specific value of 40°C .

Keywords: adhesion; damage mechanics; fibre/matrix bond; glass fibres; mechanical properties.

1 Introduction

Owing to their high strength, low weight ratio, high stiffness, and low chemical corrosiveness, structural composites are widely used as indispensable components in

many industries such as defence, aerospace, automotive, and marine. Composite materials also have great importance in different applications because of their high capability of bonding and mounting. The investigation and detection of the mechanical features of adhesives as a binder in the layered reinforced fibre composite materials have attracted considerable research attention. Moreover, the types of applications of adhesives in composite joints increase dramatically. Therefore, many researches concerning adhesive bonding techniques have been reported.

In order to determine the mechanical properties of adhesively bonded joints that combine two surfaces of different parts, several investigations have been performed, such as developing analytical models, tapering the adherents, changing the bonded lap joint geometry, and forming the adhesive fillets [1–7]. In addition to those, some scientists have also done experimental researches on bonded/bolted joints to predict the load-sharing status between the fasteners [8–11]. Kihara et al. [12] developed an experimental equipment that consists of regular hexagonal prism and two rectangular plates, and applied impact loads via the equipment. The results were also compared with those obtained from finite element method (FEM). Vaidya et al. [13] determined the failure characteristics of adhesively bonded joints under the effect of transverse impact loading. Yang et al. [14] proposed an analytical model to obtain the strain-stress distribution of adhesively bonded composite joints under tension. Sayman et al. [15] performed an elastic-plastic stress analysis using theoretical and numerical methods, and obtained a good agreement between the two methods. Kim et al. [16] carried out experimental and numerical analysis to find damage modes resulting from out-of-plane impact loads. Sayman et al. [17] studied analytical and numerical elastic-plastic stresses in a ductile adhesively bonded single-lap composite joint. Her [18] performed stress analysis in single- and double-lap joints analytically and numerically. Keller and Vallee [19] implemented experimental and numerical researches for obtaining the effects of geometrical parameters on the joint strength. Osanai and Reis [20] investigated the influence of various factors on the shear resistance of bonded joints. Avilla and Bueno Plinio

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de [21] studied experimentally a new design of adhesively bonded joints called wavy-lap joints. Aktas and Polat [22] proposed a method for improving the strength of single-lap pinned composite joints. Sayman et al. [23] investigated failure analysis of adhesively bonded composite joints under transverse impact and different temperatures. Loctite-9466 was used for joining the adherents. Testing temperatures were applied as -20°C , 23°C , 50°C , and 80°C . The impact loads were adjusted to have 5, 10, 15, and 20 J energy values. Bouchikhi et al. [24] detected reductions in interfacial stresses when using bonded laminates in strengthening existing structures. They used mixed adhesive joints between the adherents and obtained lower interfacial stresses. Goeij et al. [25] investigated composite adhesive joints under cyclic loading. They compared adhesive joints under static and fatigue failures. Arikan et al. [26] determined the effects of hole drilling at different temperatures on single-lap adhesively bonded joints. They also prepared five different hole-drilling forms, and they compared these forms at different temperatures.

The authors of several papers published up to the present seem to be mostly interested in geometrical, material, and environmental parameters affecting the mechanical behaviour of joints. Among all of the factors, the loading history of joints may be the most prominent one influencing the joint endurance limit and stiffness. Therefore, the effects of various types of earlier loading, such as previously applied impacts, need to be investigated more comprehensively. This experimental research gives information about the later behaviour of joints between epoxy matrix composites under the influence of preliminary executed impacts. In this context, E-glass fibre-reinforced composite plates were fabricated by vacuum-assisted resin infusion method (VARIM), and these plates were bonded to each other using the commercially available adhesive material DP-460. Up to five times repeated impacts having different energy levels were applied to the bonded joints at various temperatures. Then, the mechanical behaviours of joints subjected to the primary-stage impact loading were investigated as a function of both the application temperature and the level of impact energy.

2 Materials and methods

In this study, E-glass fibre-reinforced composite plates were fabricated by using VARIM. The fibre fabrics composed of eight layers were prepared according to the dimensions of 1.5-m height and 2-m width, and they were spread out on the VARIM table with an angle of between 0° and 90° . After laying the resin distribution medium and

separator layer, all of these materials were then wrapped hermetically with a vacuum bagging film, and a 0.1 MPa constant pressure was applied. The epoxy resin impregnated into the bag under vacuum was cured for 3 h at 100°C . The mechanical properties of the epoxy resin matrix material are given in Table 1.

The produced composite plate shown in Figure 1 was cut into $100 \times 25 \text{ mm}^2$ pieces to form rectangular adherends. The test specimens were established by bonding these rectangular samples to each other using the commercial epoxy adhesive material DP-460 (3M Comp., St. Paul, MN, USA). The bonding surfaces of the prepared specimens shown in Figure 2 were $25 \times 25 \text{ mm}^2$.

After the adhesive materials were cured at room temperature for at least 6 h, various grades of axial impacts with 0, 5, 10, 15, and 20 J energy levels were practiced on these specimens at different temperatures (-20°C , 0°C , 20°C , 40°C , and 60°C). Beta F50 Fast Freezer Spray (BETA Chemistry, Esenyurt-Istanbul, Turkey) was used for cooling the system, and high-capacity resistors were designed for heating. Four specimens were tested for each combination of temperature and energy value, and the average values were used in the results of experimental analysis. The instantaneous temperature value on the joint region was measured using an infrared thermometer (Fluke), and $\pm 2^{\circ}\text{C}$ temperature deviations were taken into consideration when carrying out the impact experiments. The axial impacts were carried out five times for each specimen, as illustrated in Figure 3.

Table 1: The mechanical properties of the matrix material (Araldite LY1564/Aradur 3486).

Tensile strength (MPa)	72
Tensile modulus (MPa)	2940

Figure 1: The fabrication of glass fibre-reinforced epoxy composite plate.

Figure 2: The geometrical illustration of the specimen with dimensions.

Figure 3: The Charpy impact tester with an axial impact adaptor.

During the impact loading tests, some specimen joints could not bear the strikes and were separated at different phases of the five repetitions. The samples that were able to withstand impact loads were secondarily tested with an MTS Model 40–300 kN tensile testing machine. Both impacts and static tensile tests were carried out completely under the same experimental conditions. The application of the high-temperature tests is shown in Figure 4. The values obtained during the secondary tensile loading were compared with each other in the following section.

3 Results and discussion

Joints formed with the DP-460 epoxy adhesive between glass fibre-reinforced epoxy matrix specimens were examined during the present experimental work. At the initial stage of the testing process, the adhesively bonded joints

Figure 4: Tensile tests performed at high temperatures via the high-capacity resistance heater.

of the composite samples were exposed to axial tensional impacts with four different energy levels (5, 10, 15, and 20 J) at five different degrees of application temperature (-20°C , 0°C , 20°C , 40°C , and 60°C). A modified Charpy impact tester with a mounting apparatus of our own design was employed to apply impact loads on joints. The impacts were repeated five times for each sample before proceeding to a secondary testing phase. The test temperatures of samples were brought to the desired levels by heating and cooling the overlapping sections of specimens locally through the use of a resistance heating tool and a manually applied freezer spray. The subsequent section of the

Figure 5: Effects of different impact energy values on load-displacement response at the -20°C temperature level.

experimental process was devoted to find out the static tensile responses of samples pre-exposed to axial impacts with gradually increased intensities. Each test specimen was loaded in tension at the corresponding temperature level at which the first-stage impact tests were performed.

The graphs generated by the tensional loadings performed at -20°C are displayed in Figure 5. This figure comprises three load-displacement diagrams, each of which is related to a particular pre-exposed energy value. These three levels of impact energies are 0 J (without impact), 5 J, and 10 J. However, the figure does not appear to include any of those subjected to 15 and 20 J impact loadings because none of them could maintain their integrity after the two highest energy level impacts implemented at -20°C , which is the lowest test temperature applied in our experiments. The impact results of different samples exposed to the 15 J energy level were such that the joints were entirely broken off at various stages, such as the second, third, and fifth repetition of impacts. Actually, a certain amount of step-wise decomposition had also been observed between the bonding surfaces after each repetition before the complete damage. On the other hand, complete ruptures were observed during the earliest impacts, unexceptionally for all of the tested specimens exposed to the 20 J energy level. The temperature-dependent brittleness of the adhesive material at low temperatures is likely to be the cause of the joint's vulnerability to impact loadings.

The knee emerging close to the 3000 N load value on the 0 J curve in Figure 5 is very noteworthy, because the specified load corresponds to an average shear stress value of maximum 4.8 MPa, which remains slightly below the given shear strength (6.9 MPa) of the DP-460 epoxy

adhesive on fiber reinforced plastic (FRP) substrates as given in Table 2 [27]. Low-temperature application is very apparently responsible for such a difference between the given shear strength and that read from the slope-change points.

Expectedly, the graphs of experiments performed at ambient temperature exhibit deflections under the force level corresponding exactly with the adhesive shear strength in Figure 6. However, the knee point decreases again in the graphs of tests performed at increased temperatures (40°C and 60°C), as observed in Figures 7 and 8. The results obtained from the experiments revealed that the change of adhesive shear strength depends on the

Table 2: Overlap shear strength of DP-460 epoxy adhesive [26].

	MPa
Galvanised steel	13.8
Cold rolled steel	19.3
FPL etched aluminium	31.0
Copper	27.6
Stainless steel	27.6
Brass	27.6
Acrylic	2.3
PVC	2.4
Polycarbonate	3.4
Neoprene/steel	0.8 ^a
SBR/steel	1.0 ^a
ABS	4.0
FRP	6.9 ^a

^aSubstrate failure. FPL, forest products laboratory; PVC, polyvinyl chloride; SBR, steel belted radius; ABS, acrylonitrile butadiene styrene; FRP, fiber reinforced plastic.

Figure 6: Effects of different impact energy values on load-displacement response at the 20°C temperature level.

Figure 7: Effects of different impact energy values on load-displacement response at the 40°C temperature level.

process temperature. Another prominent factor being measured and affecting shear stress is the magnitude of axial impact, which is primarily applied to the joint at the same temperature as that in tensile loading. Interestingly, 5 and 10 J impacts were observed to elevate the shearing stresses in -20°C applications, even though the ultimate joint strengths were decreased. Such an increase is most probably associated with the occurrence of further embrittlement due to cooling the adhesive layer one or more extra times during impact loading. Nonetheless, the load values corresponding to the knee points of curves decreased incrementally for each increase of impact intensity in the tests performed at the other temperature levels (0°C, 20°C,

40°C, and 60°C). It may not exactly mean the decline in shear strengths in connection with the magnitude of axial impact energy, as the gradual reduction of the adhesive bonding zone after each repetition of impacts could be monitored clearly from the interfacial colour change.

Initially, the joints were able to endure 20 J impact loads during the first four repetitions performed at the application temperature of 0°C; however, later, they became disjoint at the fifth strike, without exception. However, unlike the situation experienced at -20°C, the joints exposed to 15 J impact at 0°C could maintain their structural integrity for the secondary quasi-static tensile testing (Figure 9). Experiments performed at 5, 10, and 15 J energy levels gave reasonable

Figure 8: Effects of different impact energy values on load-displacement response at the 60°C temperature level.

Figure 9: Effects of different impact energy values on load-displacement response at the 0°C temperature level.

failure loads at this temperature, although the values are too close together. Notwithstanding, the joint stiffness and distance to failure values do not seem to display a specific variation in proportion to the impact energies at the temperature level of 0°C. This uneven load displacement curve behaviour is probably due to the exposure of more than the anticipated number of parameters on impact damage. Incompatible interfacial crack propagation during collision and rapid interaction with the ambient temperature in hot and cold applications are potential factors interacting with the current tensile responses.

In terms of stiffnesses and maximum tensile elongations, experiments performed at room temperature also

gave irregular load-displacement curves for different impact value applications, as demonstrated in Figure 6. This phenomenon appears to be also the same as that witnessed in the experiments performed at any testing temperature level currently applied. As seen in the figure, the failure load is the highest for the 20 J energy level due to the residual stresses that occurred in the specimen after repeated impact loading.

In the present circumstance, however, only failure loads in general seem to act in a particular manner depending on the impact load intensity. In addition to the failure load declines, impacts applied at 40°C considerably reduced the failure distances between the rates

of 50% and 70% (Figure 7). The specified displacements were also observed to be directly proportional to the damage loads. Thus, the impacts are more detrimental on the tensile properties of joints over the room temperature conditions.

Elevated temperature causes much more damage than that of moderate degrees during the collision. Furthermore, the influence of impact load may be less detectable at higher temperatures because the adhesive material becomes extremely soft and ductile, so it will not allow any crack formation. The case mentioned above can be easily inspected in Figure 8 from the similarity of curves related to the specimens impacted at four different energies and the unimpacted specimens. At the temperature application of 60°C, as well, the curves slightly loose linearity beyond the knee points, relative to the lower temperature curves discussed earlier. The situation indicates a continuous yielding in adhesive layer before reaching the final breakup point because of the excessive temperature exposure.

Axial loading failure values influenced by both high- and low-temperature applications, and impact magnitudes are graphically illustrated in Figure 10. Based on the temperature level tested during both the impact and tensile loadings, the tensile shearing strengths of joints seem to be affected significantly in different ways. At room temperature, the 5 J impact reduced the failure value to some extent, and the shearing resistance was slightly reduced step by step after each increase of impact energy (or velocity). In fact, this situation is a well-known and anticipated behaviour for such joints. At low-temperature conditions, the observable response of joints seemed to be also in a similar manner, and the reduction rate of failure load with increased impact energy did not change

to a large extent. Additionally, lower failure values were monitored for each increase of impact energy level at low temperatures. Due to embrittlement at low temperatures, some high-energy-level impacts also caused abrupt failures in the joints during collision at various phases of five repetitions. Because of these early-stage fractures, secondary tensile tests could not be implemented after 15 and 20 J impacts at -20°C and 20 J impacts at 0°C. On the other hand, high-temperature tests performed at 40°C gave interesting results in terms of failure load values. At this temperature, impacted joints exhibited higher strengths than those tested without receiving any previous impact (0 J). Furthermore, the failure strength also kept increasing while the energy of impact load was raised. This phenomenon can be attributed to a special kind of work hardening as a result of permanent plastic deformation in the adhesive layer. This strengthening effect of axial impact loads at specific degrees of temperatures may be used to improve the future bonded joint designs. However, temperatures higher than this specific value do not affect in a positive way. Joints could exhibit minimum endurance limits after exposure to the impact loads performed at 60°C.

Post-failure photos of specimens are given in Figure 11. According to the crack surfaces observed, the joints were separated with both adhesive and adherend failure types. It appears that high-temperature softening of the adhesive layer caused adhesive bonds to degrade, and for this reason, adhesive type failure was generally monitored on the sample crack surfaces of those tested at 60°C. As the test temperature was decreased to lower degrees, the failure type also seemed to transform incrementally from adhesive type to adherend type, which occurs inside the epoxy matrix or in the fibre-matrix interface.

Figure 10: Failure load variations with respect to impact load energy and application temperature.

Figure 11: Photos of failed specimens: (A) -20°C, (B) 0°C, (C) 20°C, (D) 40°C, and (E) 60°C.

4 Conclusion

The effects of five times repeated axial impacts on single-lap adhesively bonded composite joints were investigated. Impacts having various energy levels (0, 5, 10, 15, and 20 J) were applied at different temperatures (-20°C, 0°C, 20°C, 40°C, and 60°C). As a result of the exposure of specimens to static tensile loading at the same temperature conditions as applied during impact loading, the following conclusions can be made:

The failure strengths of composite joints are strongly related to the impact history. With one exception, further debilitation takes place in joints as the impact energy is increased.

Axial impacts at low temperatures are more detrimental to axial failure strengths of bonded composite joints, and each fall in temperature level during impacts causes additional strength loss.

A low-temperature environment makes joints more susceptible to impact load. None of the joint samples was able to maintain the integrity after 20 J impact at 0°C, and 15 and 20 J impacts at -20°C.

Impacts at high temperatures give dissimilar results according to the temperature level. While the impact loads applied at 60°C weakened the joints, considerably those applied at 40°C gave joints extra endurance. At this special temperature, higher impact energies cause unexpected improvement in joint strengths. The strength was increased at 40°C with the increase in ductility because the impact energy absorption of the adhesive material was increasing with the increasing temperature. However,

the strength of the adhesive material that was exposed to impact energy spontaneously decreased as the adhesive material became an amorphous structure at 60°C.

References

- [1] da Silva LFM, das Neves PJC, Adams RD, Spelt JT. *Int. J. Adhesion Adhesives* 2009, 29, 319–330.
- [2] da Silva LFM, das Neves PJC, Adams RD, Wang A, Spelt JT. *Int. J. Adhesion Adhesives* 2009, 29, 331–341.
- [3] Goyal VK, Johnson ER, Goyal VK. *Compos. Struct.* 2008, 82, 434–446.
- [4] da Silva LFM, Ochsner A, Adams RD, *Handbook of Adhesion Technology*, Springer: Heidelberg, 2011.
- [5] Beylergil B, Cunedioglu Y, Aktas A. *Compos. Pt. B* 2011, 42, 1885–1896.
- [6] Gultekin K, Akpinar S, Ozel A. *Compos. Pt. B* 2014, 60, 736–745.
- [7] Soykok IF. *Compos. Pt. B* 2015, 77, 129–138.
- [8] Matzusaki R, Shibata M, Todoroki A. *Compos. Pt. A* 2008, 39, 154–163.
- [9] Bodjona K, Raju K, Lim GH, Lessard L. *Compos. Struct.* 2015, 129, 268–275.
- [10] Bodjona K, Raju K, Lim GH, Lessard L. *Compos. Struct.* 2015, 129, 276–283.
- [11] Kelly G. *Compos. Struct.* 2005, 69, 35–43.
- [12] Kihara K, Isono H, Yamabe H, Sugibayashi T. *Int. J. Adhesion Adhesives* 2003, 23, 253–259.
- [13] Vaidya UK, Gautam ARS, Hosur M, Dutta P. *Int. J. Adhesion Adhesives* 2006, 26, 184–198.
- [14] Yang CD, Huang H, Tomblin JS, Sun WJ. *J. Compos. Mater.* 2004, 38, 293–309.
- [15] Sayman O, Ozen M, Korkmaz B. *Mater. Des.* 2013, 45, 31–35.
- [16] Kim H, Kayir T, Mousseau SL. *J. Compos. Mater.* 2005, 39, 2039–2052.

- [17] Sayman O, Ozen M, Ozel A, Demir T, Korkmaz B. *Sci. Eng. Compos. Mater.* 2012, 20, 163–168.
- [18] Her SC. *Compos. Struct.* 1999, 47, 673–678.
- [19] Keller T, Vallee T. *Compos. Pt. B* 2005, 36, 331–340.
- [20] Osanai KR, Reis JML. *Thermal Eng.* 2012, 11, 4.
- [21] Avilla AF, Bueno Plinio de O. *Compos. Struct.* 2001, 64, 531–537.
- [22] Aktas A, Polat Z. *J. Compos. Mater.* 2010, 44, 2919–2928.
- [23] Sayman O, Arikan V, Dogan A, Soykok IF, Dogan T. *Compos. Pt. B* 2013, 54, 409–414.
- [24] Bouchikhi AS, Megueni A, Gouasmi S, Boukoulda FB. *Mater. Des.* 2013, 50, 893–904.
- [25] Goeij WC, Tooren MJL, Beukers A. *Mater. Des.* 1999, 20, 213–221.
- [26] Arikan V, Dogan A, Dogan T, Sabanci E, Al-Shamary AKJ. *J. Adhesion* 2015, 91, 177–185.
- [27] 3M Scotch-Weld epoxy adhesives. Available at <http://multimedia.3m.com/mws/media/661220/3mtm-scotch-weld-tm-epoxy-adhesive-dp460-ns-and-off-white.pdf>. Accessed 13 November, 2015.